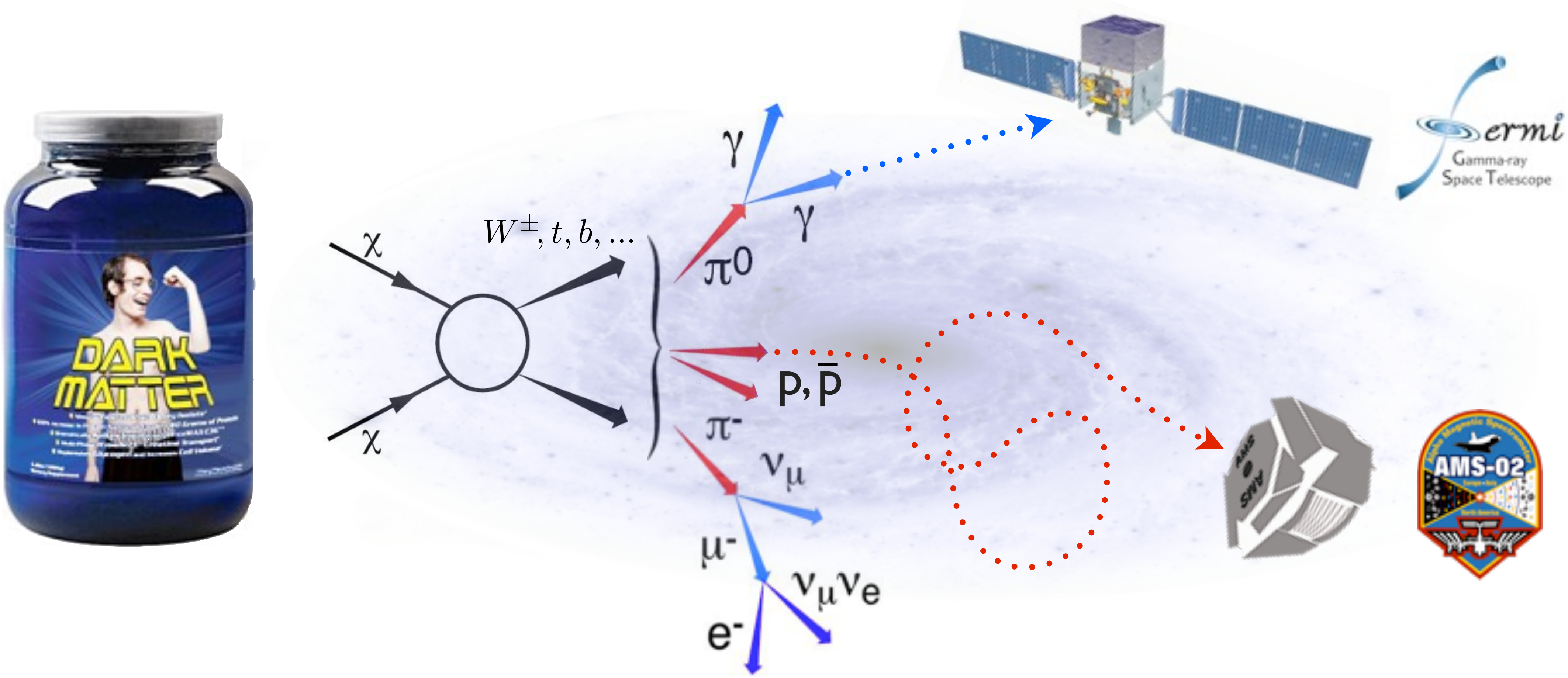
Probing dark matter annihilation in the Galaxy with antiprotons and gamma rays

[based on A. Cuoco, JH, M. Korsmeier, M. Krämer: 1704.08258
and A. Cuoco, M. Korsmeier, M. Krämer: 1610.03071]

Jan Heisig (RWTH Aachen University)

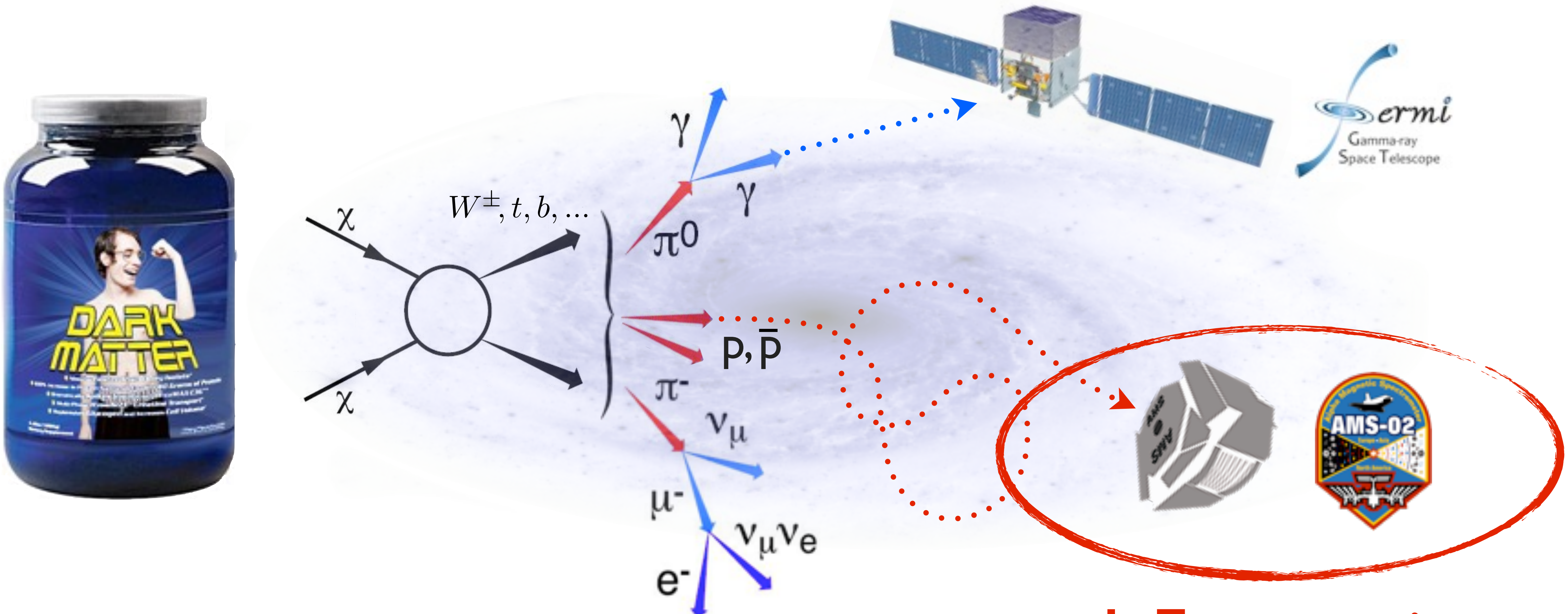
TTK Institute for Theoretical Particle Physics and Cosmology | RWTH AACHEN UNIVERSITY

Dark matter indirect detection: antiprotons and gamma rays



- Dark matter searches joint effort
- Indirect detection probes annihilation
- AMS-02: cosmic-ray precision era

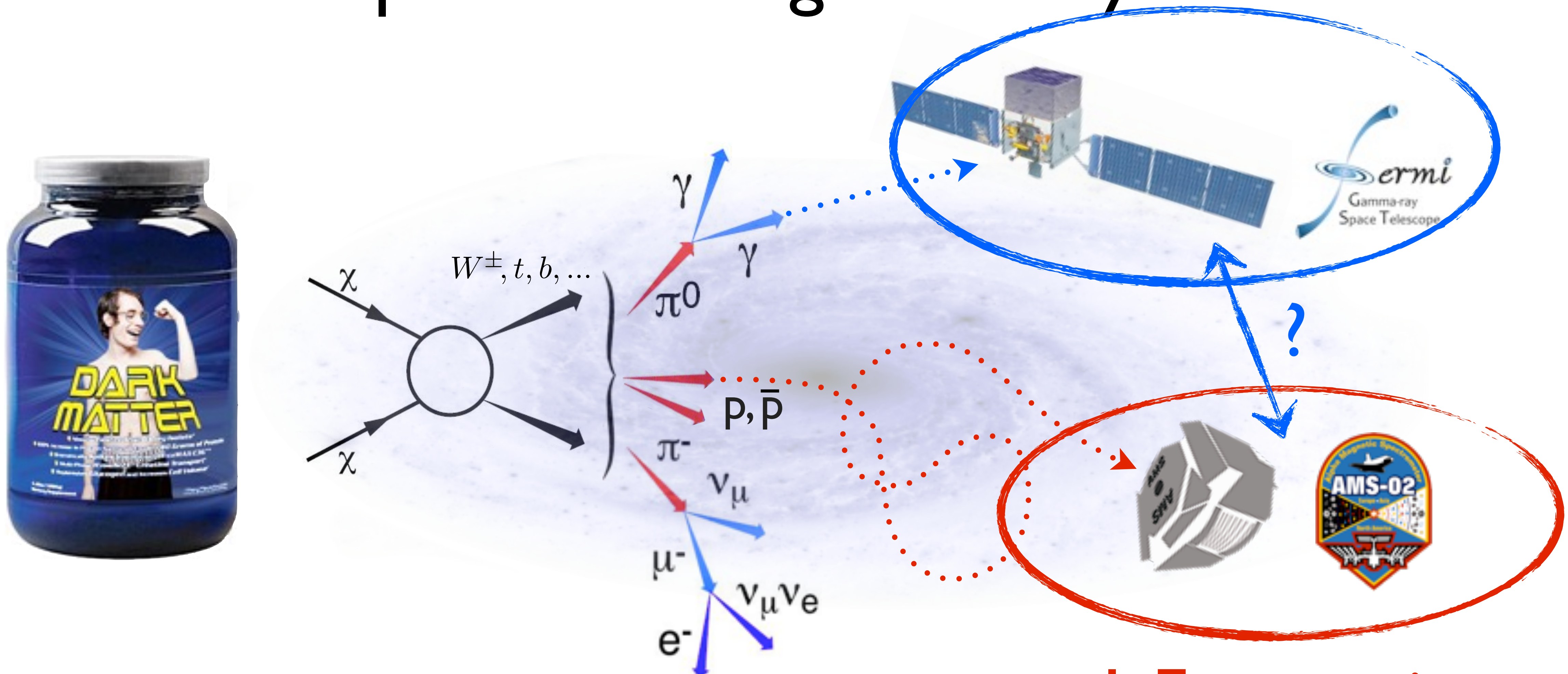
Dark matter indirect detection: antiprotons and gamma rays



I. Feature in AMS antiprotons

- Dark matter searches joint effort
- Indirect detection probes annihilation
- AMS-02: cosmic-ray precision era

Dark matter indirect detection: antiprotons and gamma rays



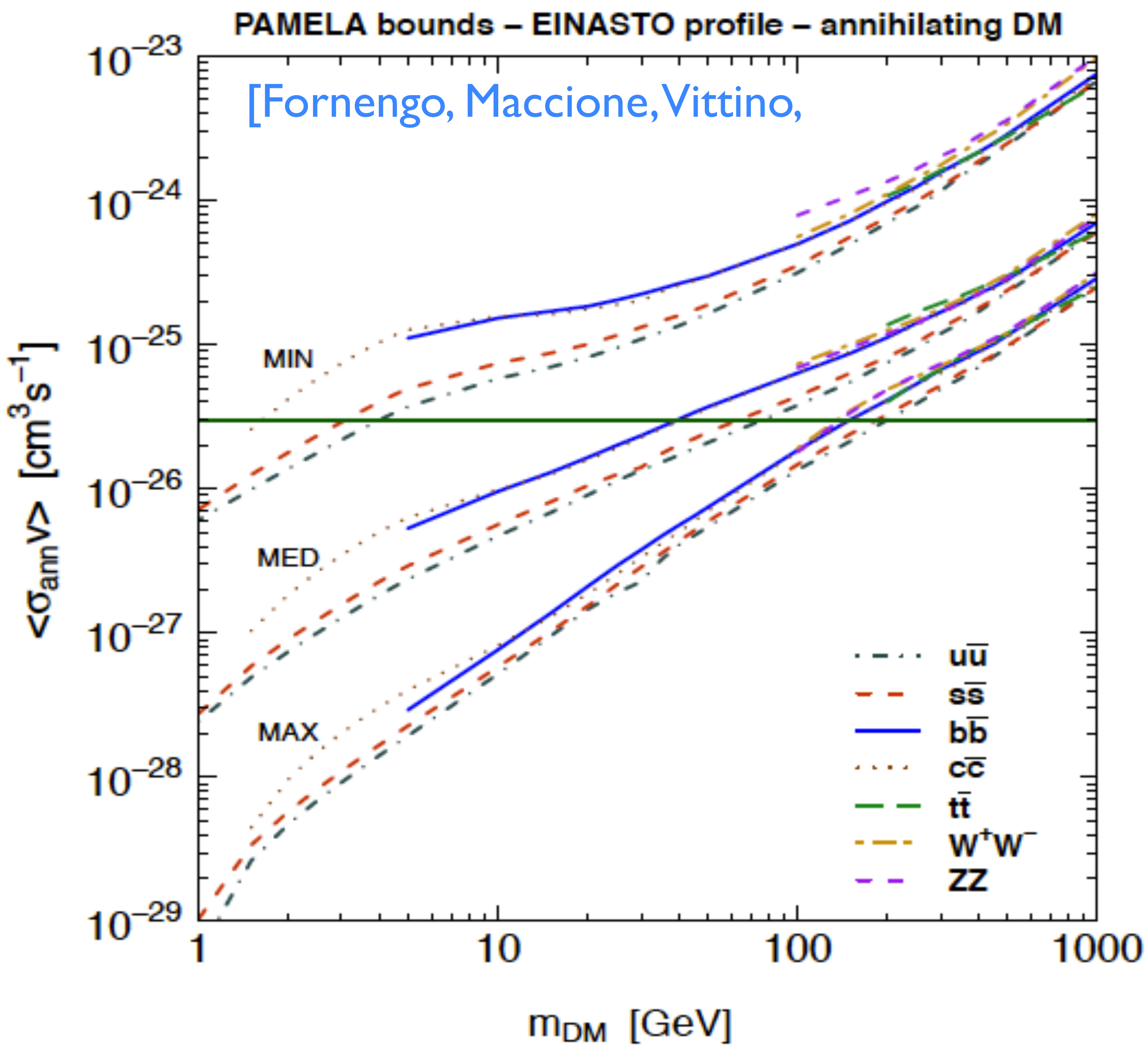
- Dark matter searches joint effort
- Indirect detection probes annihilation
- AMS-02: cosmic-ray precision era

I. Feature in AMS antiprotons

II. Implications for dark matter models

1. Feature in AMS antiprotons

Searches for dark matter in cosmic-rays



[see e.g. L. Bergstrom, J. Edsjo, and P. Ullio, ApJ,526,215 (1999); F. Donato, N. Fornengo, D. Maurin, and P. Salati, PRD69, 063501 (2004); T. Bringmann and P. Salati, PRD75, 083006 (2007); F. Donato, D. Maurin, P. Brun, T. Delahaye, and P. Salati, PRL. 102, 071301 (2009); N. Fornengo, L. Maccione, and A. Vittino, JCAP1404,003; D. Hooper, T. Linden, and P. Mertsch, JCAP 1503, 021; V. Pettorino, G. Busoni, A. De Simone, E. Morgante, A. Riotto, and W. Xue, JCAP 1410, 078 (2014); M. Boudaud, M. Cirelli, G. Giesen, and P. Salati, JCAP1505, 013 (2015); J. A. R. Cembranos, V. Gammaldi, and A. L. Maroto, JCAP 1503, 041 (2015); M. Cirelli, D. Gaggero, G. Giesen, M. Taoso, and A. Urbano, JCAP 1412, 045 (2014); T. Bringmann, M. Vollmann, and C. Weniger, Phys. Rev. D90, 123001 (2014); G. Giesen, M. Boudaud, Y. Genolini, V. Poulin, M. Cirelli, P. Salati, and P. D. Serpico, JCAP 1509, 023 (2015); C. Evoli, D. Gaggero, and D. Grasso, JCAP 1512, 039]

- MIN/MED/MAX scenario: Large uncertainties

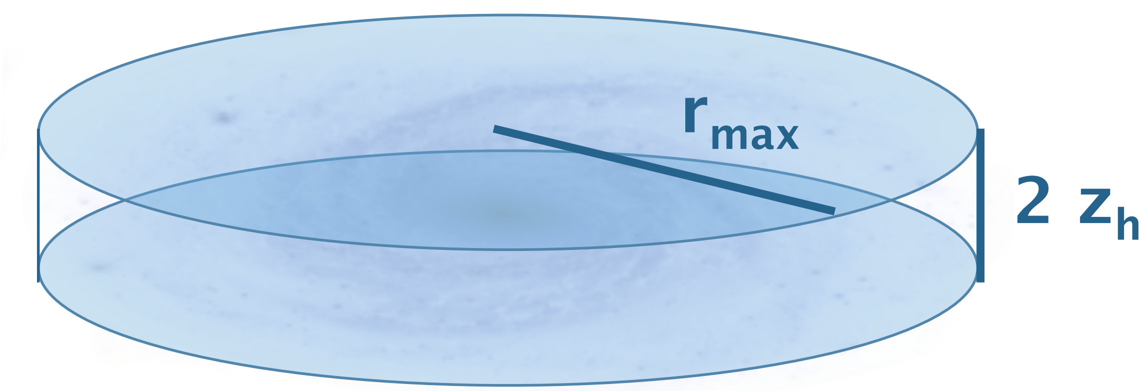
⇒ Joint fit of propagation parameters using precise AMS-02 data

Cosmic-ray propagation in the Galaxy

- Numerically solve diffusion equation:
  [using Galprop (or Dragon)]

$$\frac{\mathrm{d}\psi}{\mathrm{d}t} = q(\boldsymbol{x}, p) + \boldsymbol{\nabla} \cdot (D_{xx} \boldsymbol{\nabla} \psi - \boldsymbol{V} \psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi$$

$$- \frac{\partial}{\partial p} \left(\frac{\mathrm{d}p}{\mathrm{d}t} \psi - \frac{p}{3} \boldsymbol{\nabla} \cdot \boldsymbol{V} \psi \right) - \frac{1}{\tau_f} \psi - \frac{1}{\tau_r} \psi$$



Figures: Credit to Michael Korsmeier

Fit parameters: z_h

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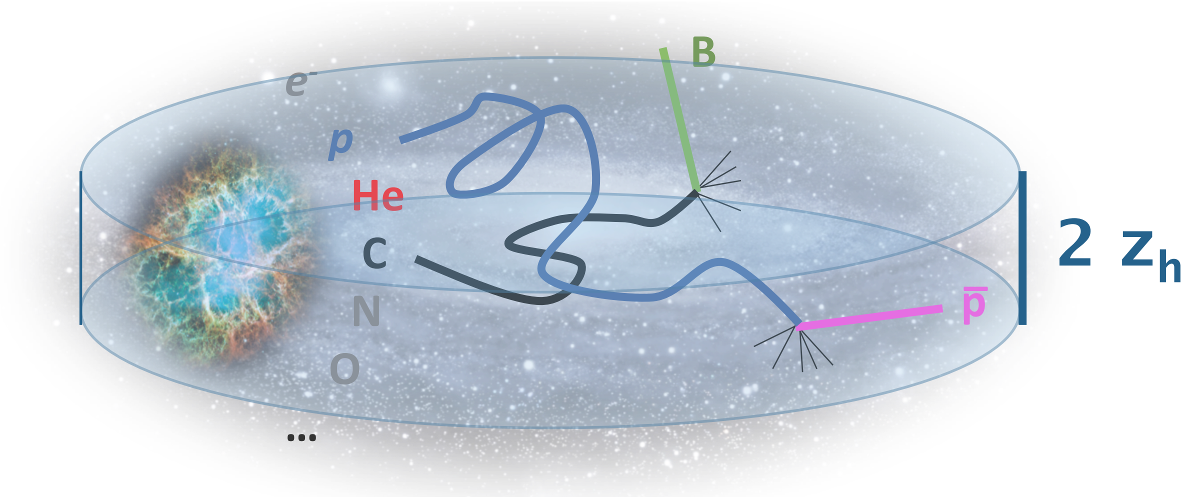
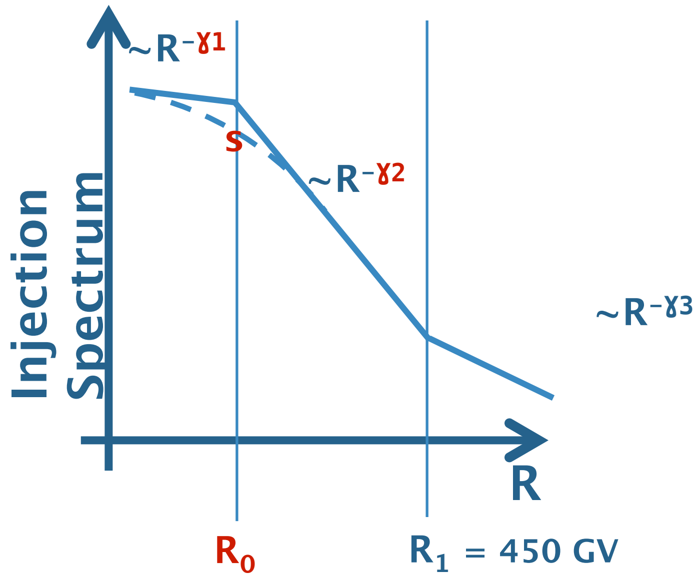


Source term - primaries:

- Astrophysical Sources:
  SNR or Pulsars
  ⇒ p, He, …

  Injection spectrum:



AMS-02 requires individual slopes for p, He!

Figures: Credit to Michael Korsmeier

Fit parameters: $z_{\mathrm{h}}, \gamma_{1,p}, \gamma_{2,p}, \gamma_1, \gamma_2, R_0, s$

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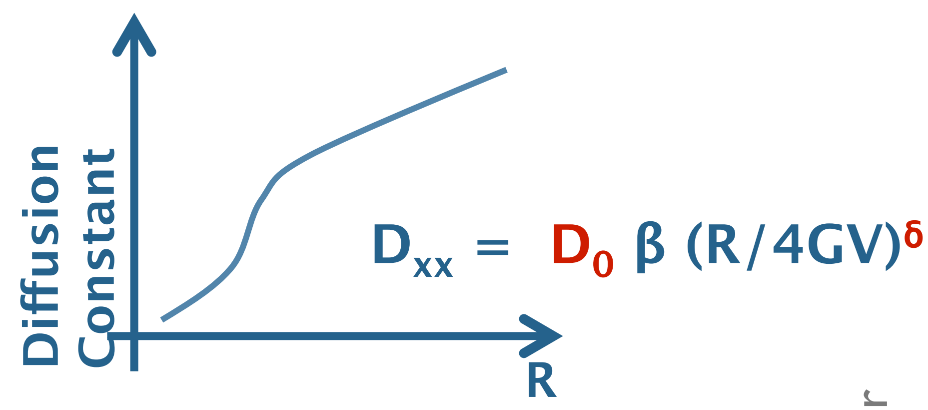
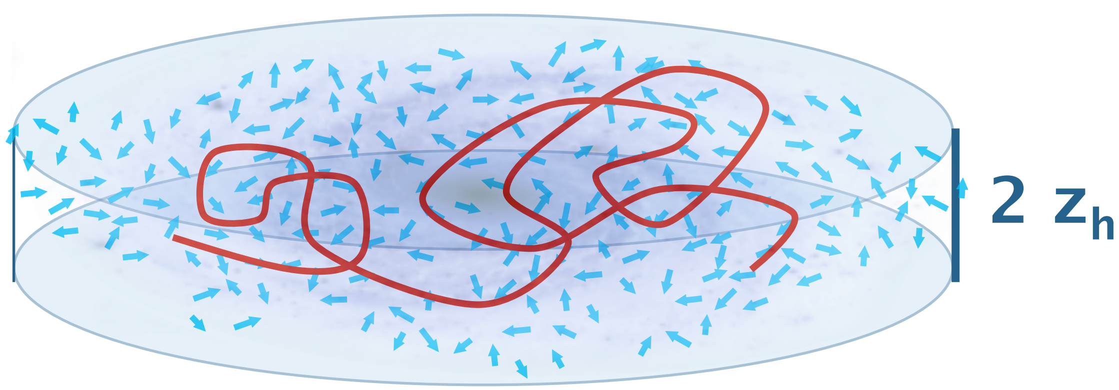
- Astrophysical Sources
- Diffusion





Figures: Credit to Michael Korsmeier

Fit parameters: $z_\mathrm{h}, \gamma_{1,p}, \gamma_{2,p}, \gamma_1, \gamma_2, R_0, s, D_0, \delta$

Cosmic-ray propagation in the Galaxy

- Numerically solve diffusion equation:
  [using Galprop (or Dragon)]

$$\frac{\mathrm{d}\psi}{\mathrm{d}t} = q(\boldsymbol{x},p) + \boldsymbol{\nabla}\cdot(D_{xx}\boldsymbol{\nabla}\psi - \boldsymbol{V}\psi) + \frac{\partial}{\partial p}p^2 D_{pp}\frac{\partial}{\partial p}\frac{1}{p^2}\psi$$
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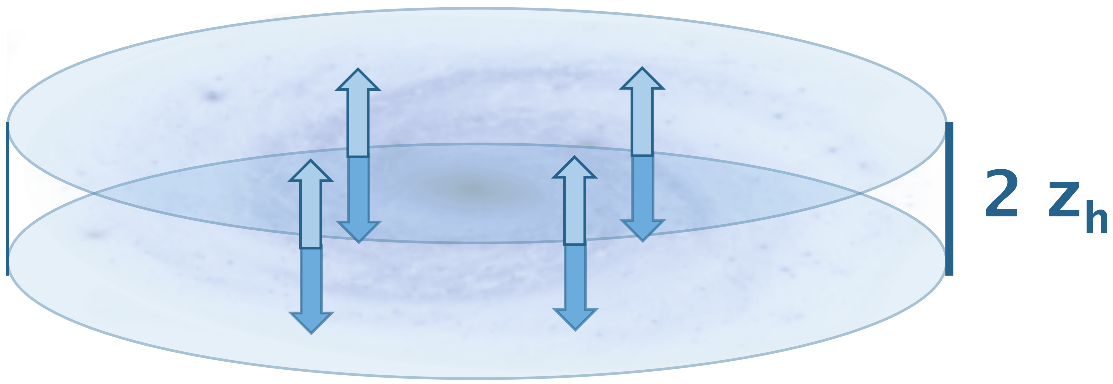
- Astrophysical Sources
- Diffusion
- Convection

  Winds perpendicular to the galactic plane
  $\mathbf{V} = v_{0,c}\, \mathrm{sign}(z)\, \mathbf{e}_z$



Fit parameters: $z_\mathrm{h}, \gamma_{1,p}, \gamma_{2,p}, \gamma_1, \gamma_2, R_0, s, D_0, \delta, v_{0,\mathrm{c}}$

Figures: Credit to Michael Korsmeier

Cosmic-ray propagation in the Galaxy

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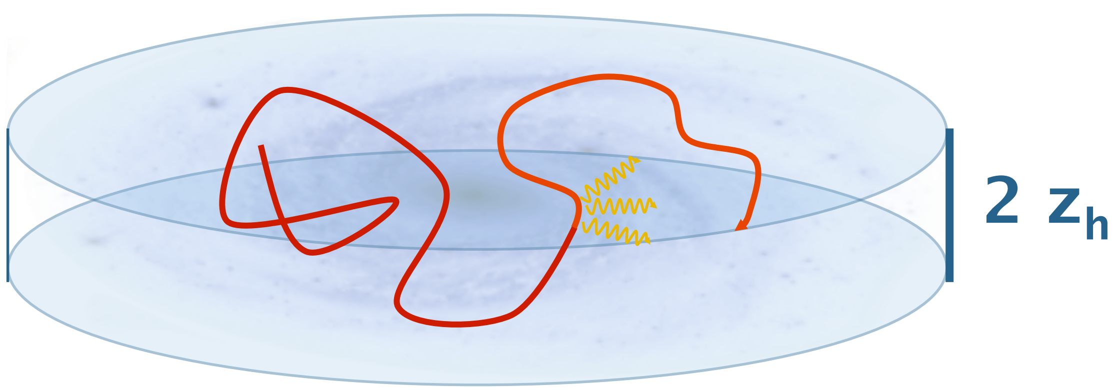
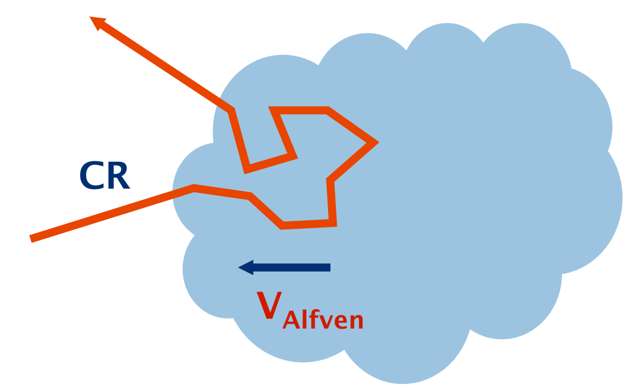


- Astrophysical Sources
- Diffusion
- Convection
- Reacceleration
  Scattering off magnetic clouds:



- Energy loss
  e.g. synchrotron radiation or ionization

Figures: Credit to Michael Korsmeier

Fit parameters: $z_{\mathrm{h}}, \gamma_{1,p}, \gamma_{2,p}, \gamma_1, \gamma_2, R_0, s, D_0, \delta, v_{0,\mathrm{c}}, v_{\mathrm{Alfen}}$

Cosmic-ray propagation in the Galaxy

- Numerically solve diffusion equation:
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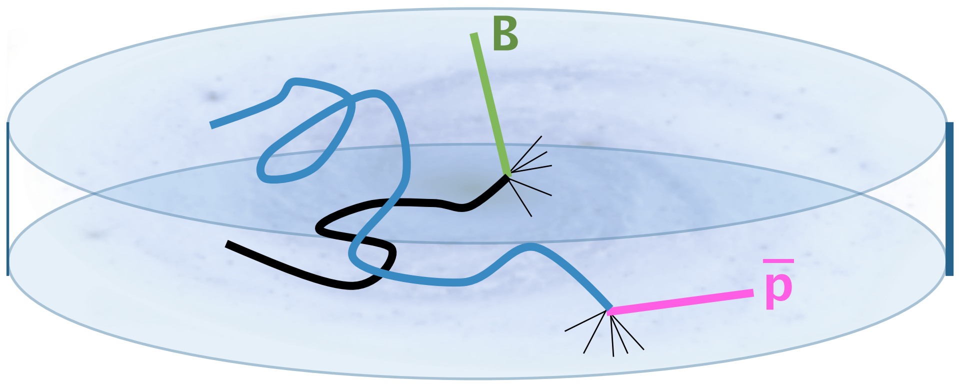


- Astrophysical Sources
- Diffusion
- Convection
- Reacceleration
- Energy loss
- Fragmentation and decay

  Loss for one species is gain for the other

  Secondaries:
  $\bar{p}$, (Li, B, …)

Figures: Credit to Michael Korsmeier

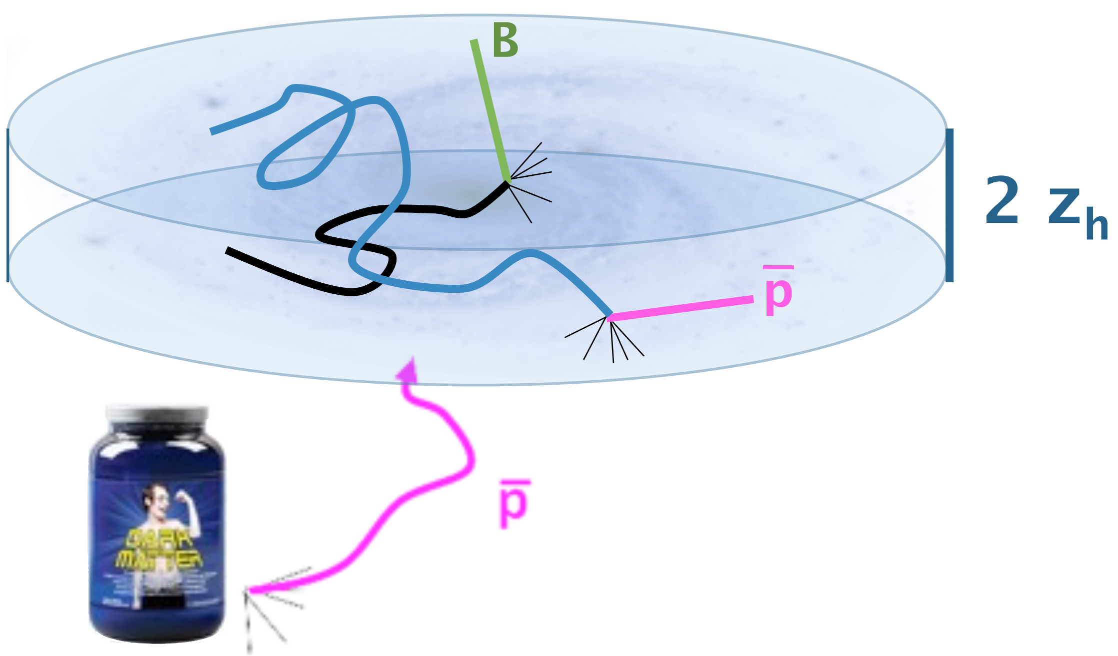
Fit parameters: $z_{\mathrm{h}}, \gamma_{1,p}, \gamma_{2,p}, \gamma_1, \gamma_2, R_0, s, D_0, \delta, v_{0,\mathrm{c}}, v_{\mathrm{Alfen}}$

Cosmic-ray propagation in the Galaxy

- Numerically solve diffusion equation:
  [using Galprop (or Dragon)]

$$\frac{\mathrm{d}\psi}{\mathrm{d}t} = q(\boldsymbol{x}, p) + \boldsymbol{\nabla} \cdot (D_{xx} \boldsymbol{\nabla} \psi - \boldsymbol{V} \psi) + \frac{\partial}{\partial p} p^2 D_{pp} \frac{\partial}{\partial p} \frac{1}{p^2} \psi - \frac{\partial}{\partial p} \left(\frac{\mathrm{d}p}{\mathrm{d}t} \psi - \frac{p}{3} \boldsymbol{\nabla} \cdot \boldsymbol{V} \psi \right) - \frac{1}{\tau_f} \psi - \frac{1}{\tau_r} \psi$$

- Astrophysical Sources
- Diffusion
- Convection
- Reacceleration
- Energy loss
- Fragmentation and decay
- Additional primary source for $\bar{p}$: Dark Matter!



Figures: Credit to Michael Korsmeier

Fit parameters: $z_{\mathrm{h}}, \gamma_{1,p}, \gamma_{2,p}, \gamma_1, \gamma_2, R_0, s, D_0, \delta, v_{0,\mathrm{c}}, v_{\mathrm{Alfen}}, \langle \sigma v \rangle_{\mathrm{DM}}, m_{\mathrm{DM}}$

Cosmic-ray propagation in the Galaxy

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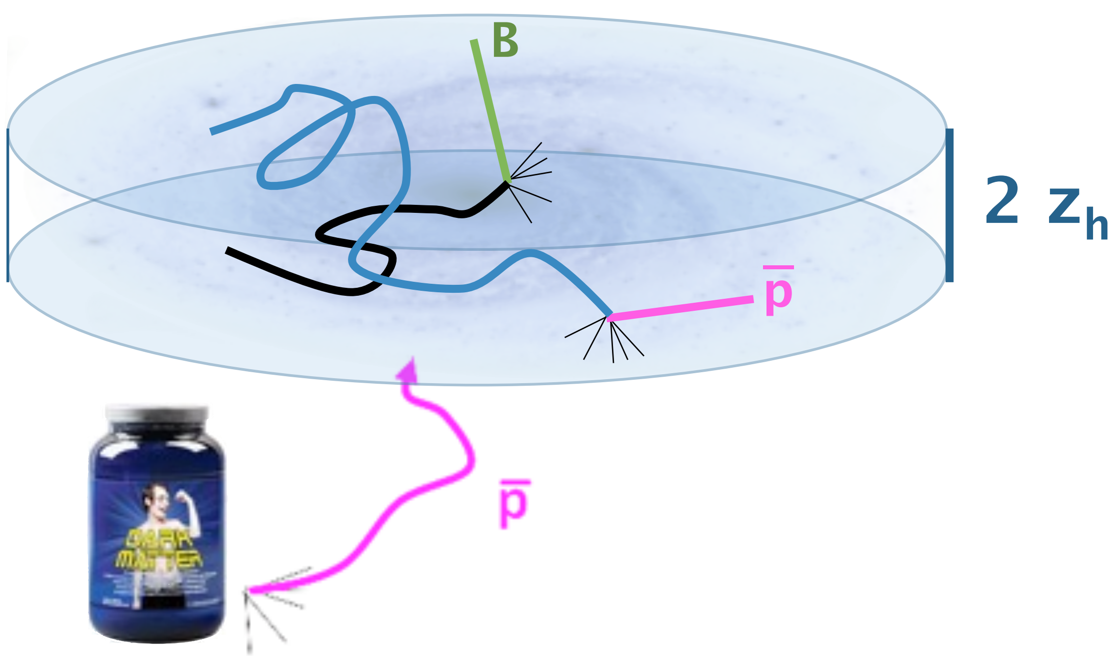


- Astrophysical Sources
- Diffusion
- Convection
- Reacceleration
- Energy loss
- Fragmentation and decay
- Dark Matter
- <u>Data:</u>
  - AMS-02: p, He, $\bar{p}$
    [AMS 2015, 2016]
  - CREAM: p, He
    [Yoon *et al.* 2011]
  - VOYAGER: p, He
    [Stone *et al.* 2013]

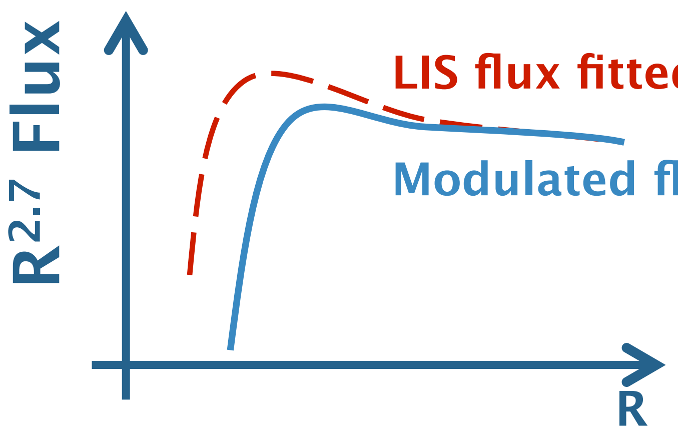
Figures: Credit to Michael Korsmeier

Fit parameters: $z_{\rm h}, \gamma_{1,p}, \gamma_{2,p}, \gamma_1, \gamma_2, R_0, s, D_0, \delta, v_{0,\rm c}, v_{\rm Alfen}, \langle\sigma v\rangle_{\rm DM}, m_{\rm DM}$

Cosmic-ray propagation in the Galaxy

Solar modulation:

- Phenomenological description: force-field approximation
- Our approach:
  - Constrain local interstellar space (LIS) flux directly by VOYAGER data
  - Exclude data below 5 GV in the main fit
  - Marginalized over ϕ_{AMS} on-the-fly for each GALPROP evaluation



- Astrophysical Sources
- Diffusion
- Convection
- Reacceleration
- Energy loss
- Fragmentation and decay
- Dark Matter
- Data:
  - AMS-02: p, He, $\bar{p}$ [AMS 2015, 2016]
  - CREAM: p, He [Yoon *et al.* 2011]
  - VOYAGER: p, He [Stone *et al.* 2013]

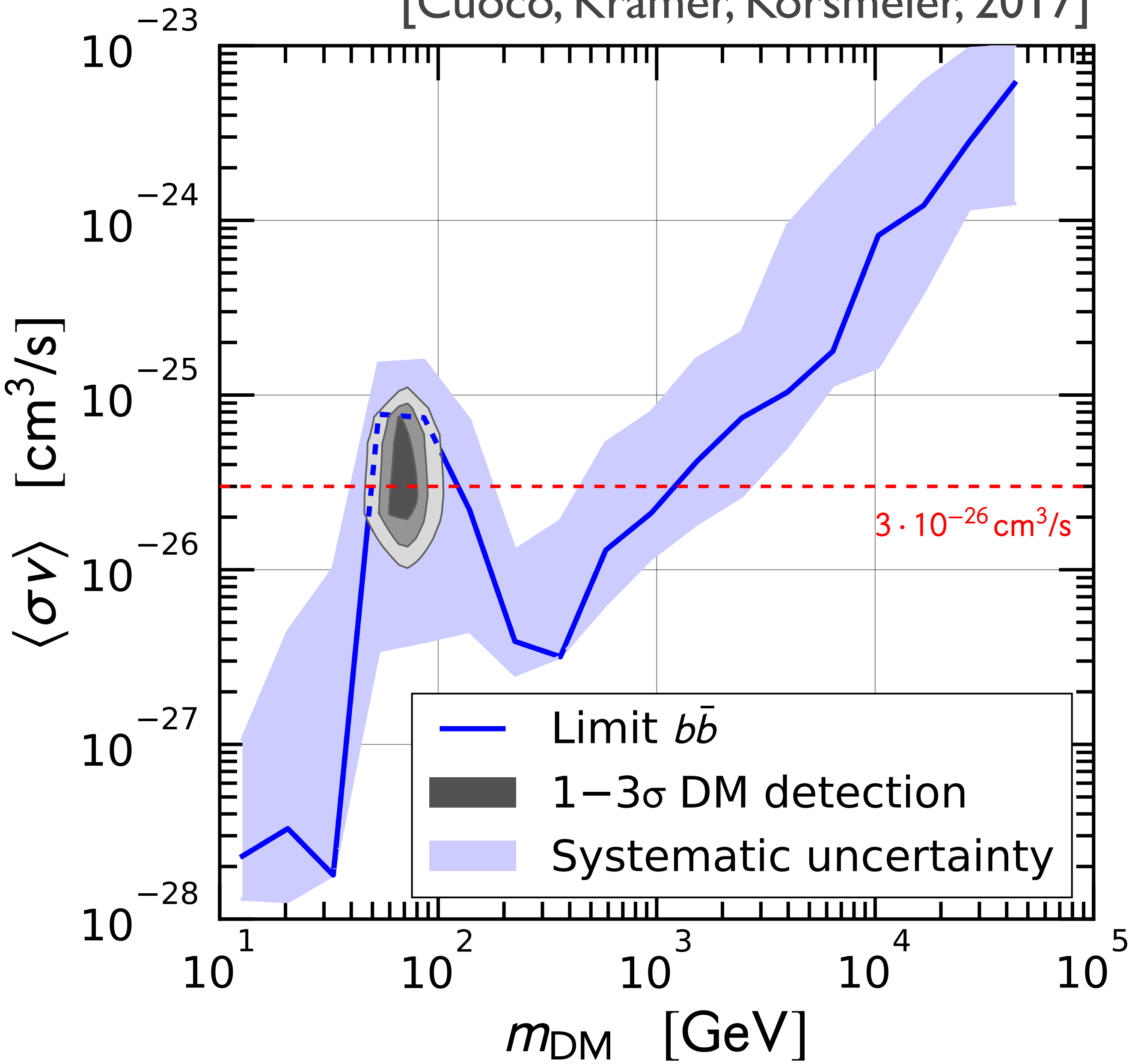
Figures: Credit to Michael Korsmeier

Fit parameters: $z_{\mathrm{h}}, \gamma_{1,p}, \gamma_{2,p}, \gamma_1, \gamma_2, R_0, s, D_0, \delta, v_{0,\mathrm{c}}, v_{\mathrm{Alfen}}, \langle\sigma v\rangle_{\mathrm{DM}}, m_{\mathrm{DM}}, (\phi_{\mathrm{AMS}})$

Cosmic-ray fit results

For 100% annihilation into *bb*:

[Cuoco, Krämer, Korsmeier, 2017]



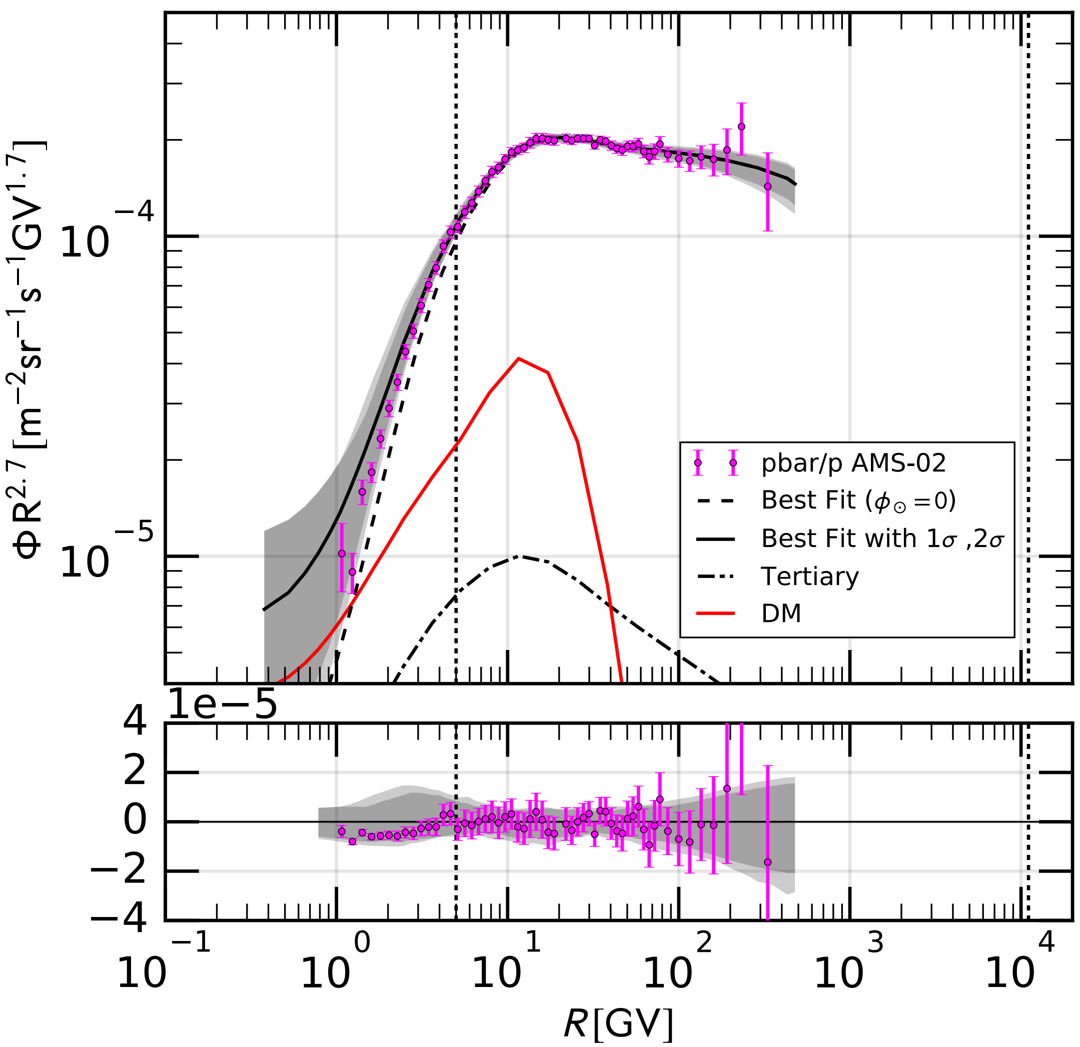
- Not able to exclude thermal cross section around 50-100 GeV
- Fit prefers additional antiprotons (with a dark matter-like injection spectrum)
- Improvement: $\chi^2/\text{d.o.f.} = 46/163\ (71/165)$ with (without) DM

⇒ Feature at 4.5σ-level (local)

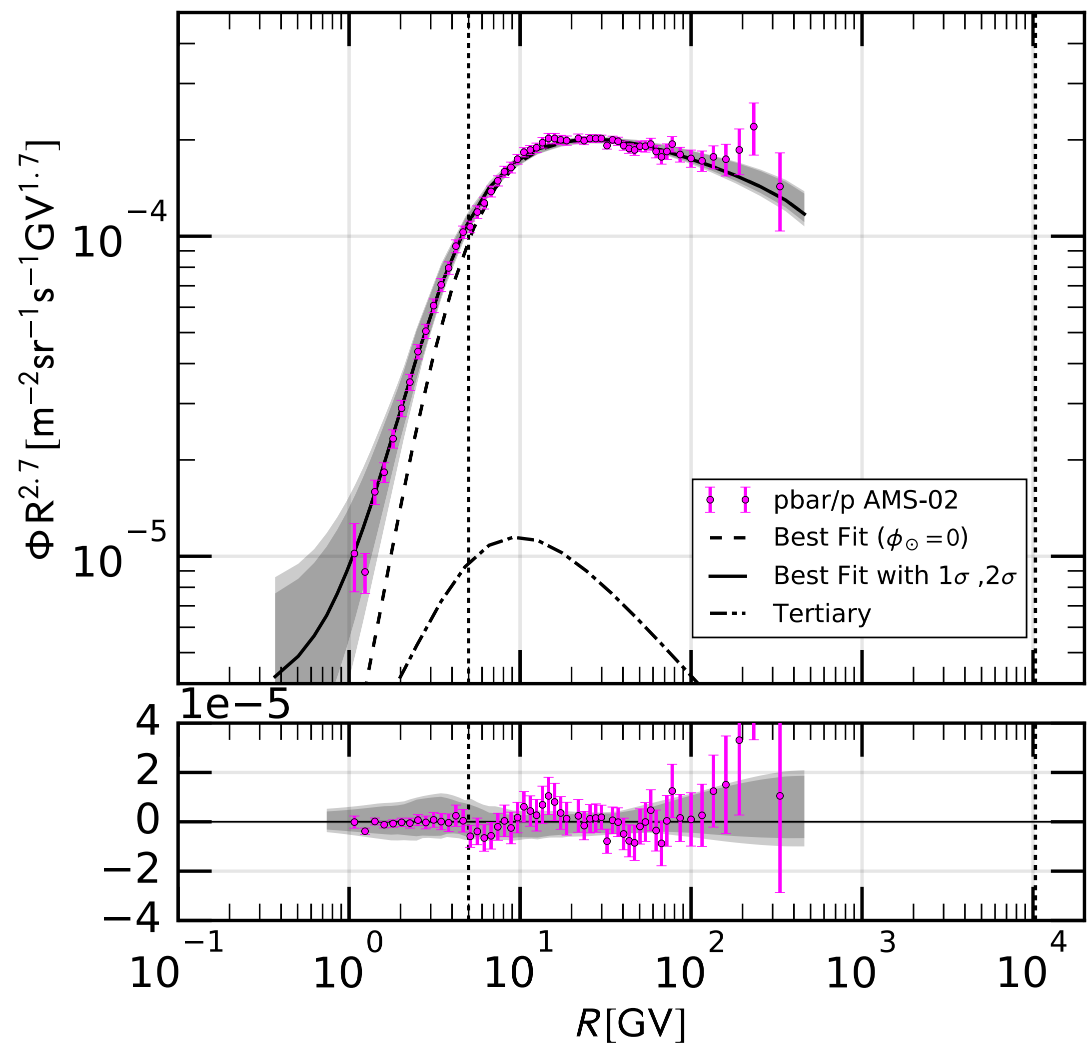
[see also Cui, Yuan, Tsai, Fan, 2017]

Cosmic-ray fit results

With dark matter (*bb*):



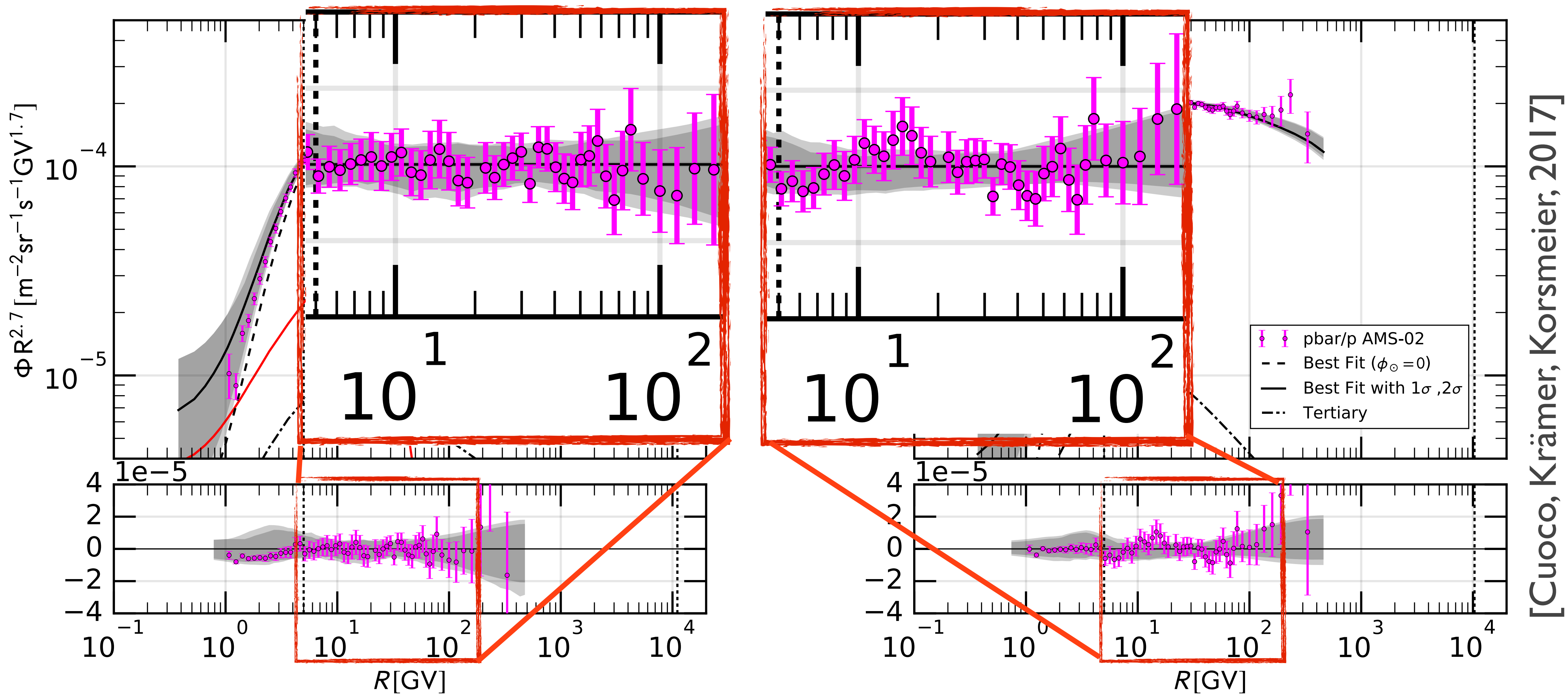
Without dark matter:



[Cuoco, Krämer, Korsmeier, 2017]

Cosmic-ray fit results

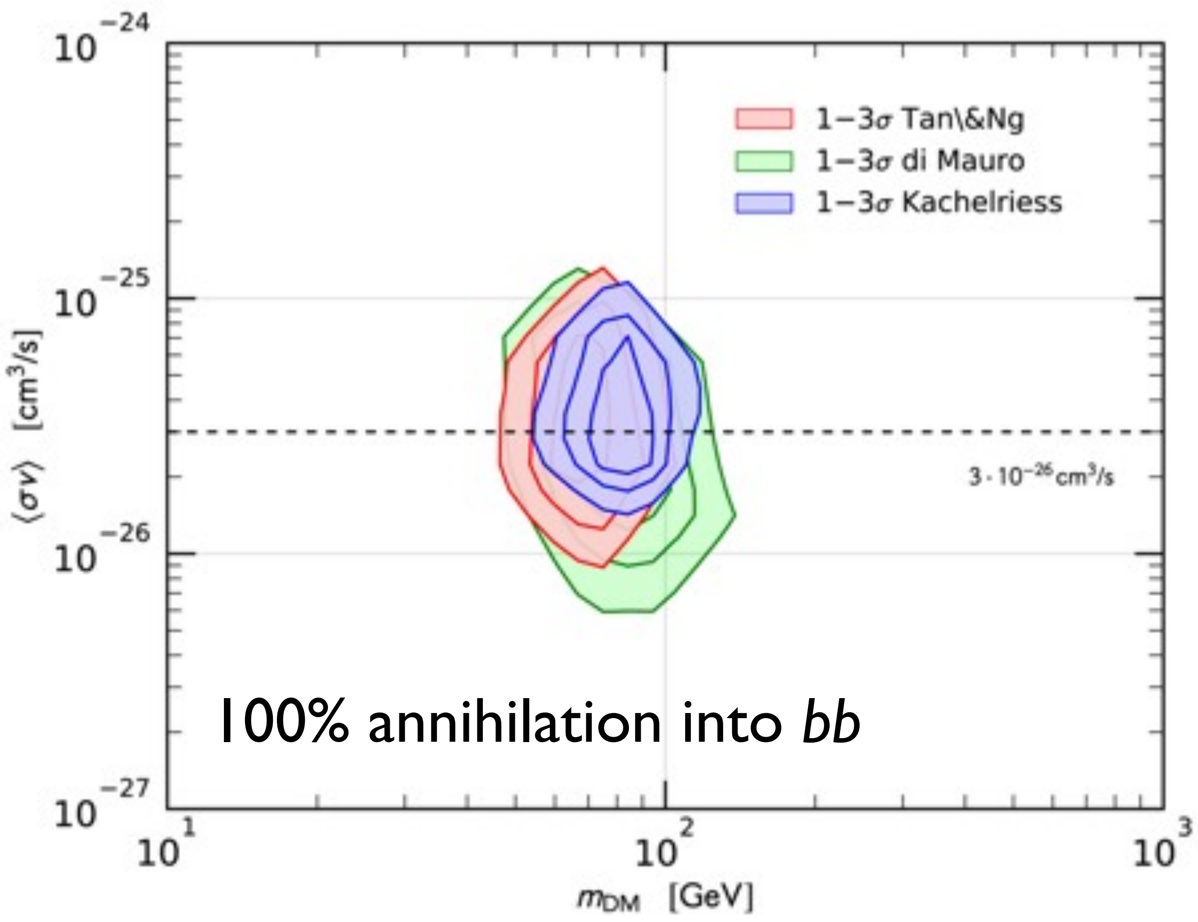
With dark matter (*bb*): | Without dark matter:



Diffusion slope: $\delta \approx 0.25$ $\delta \approx 0.36$

Sources of systematic uncertainties

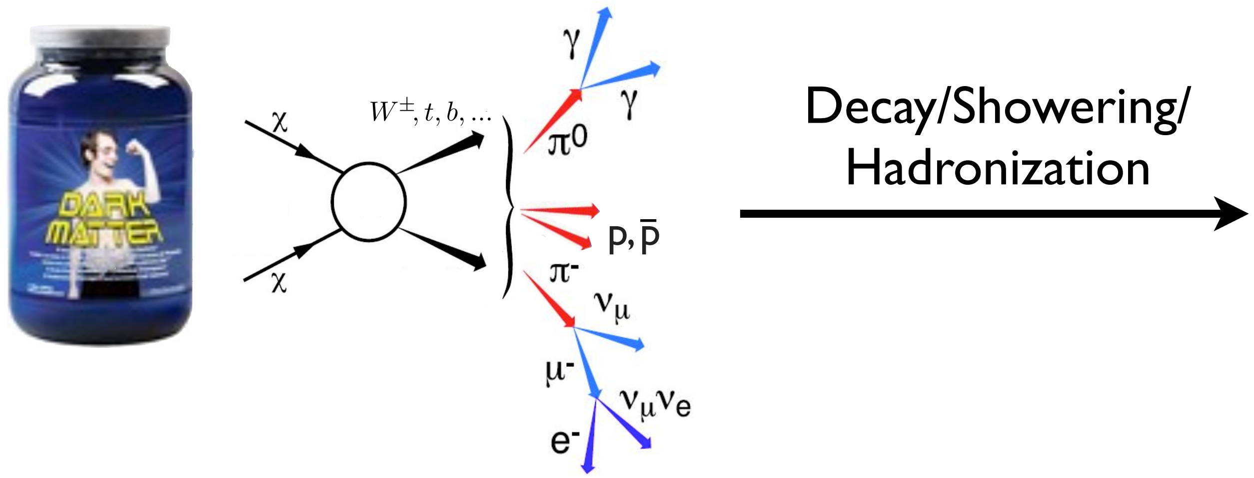
Dependence on the antiproton cross section:

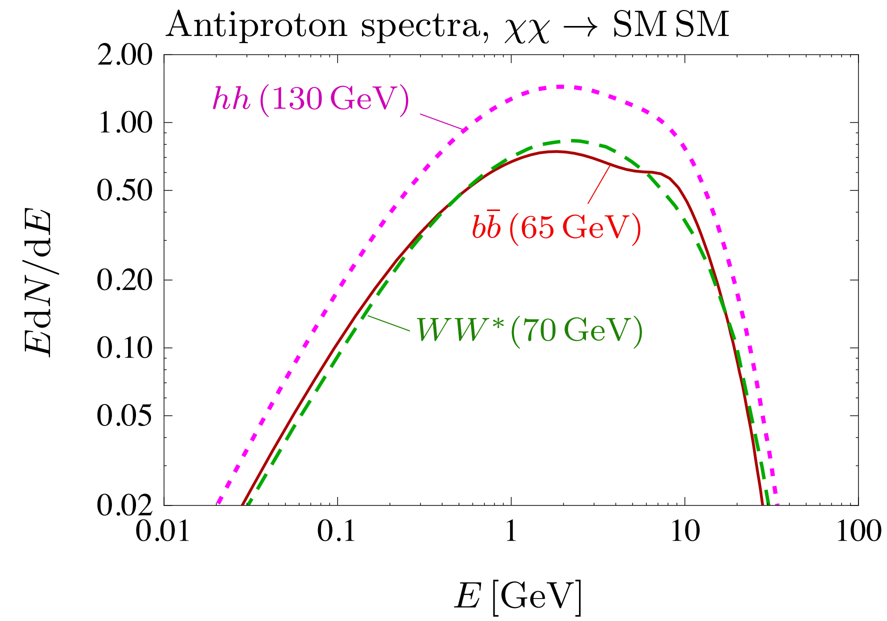


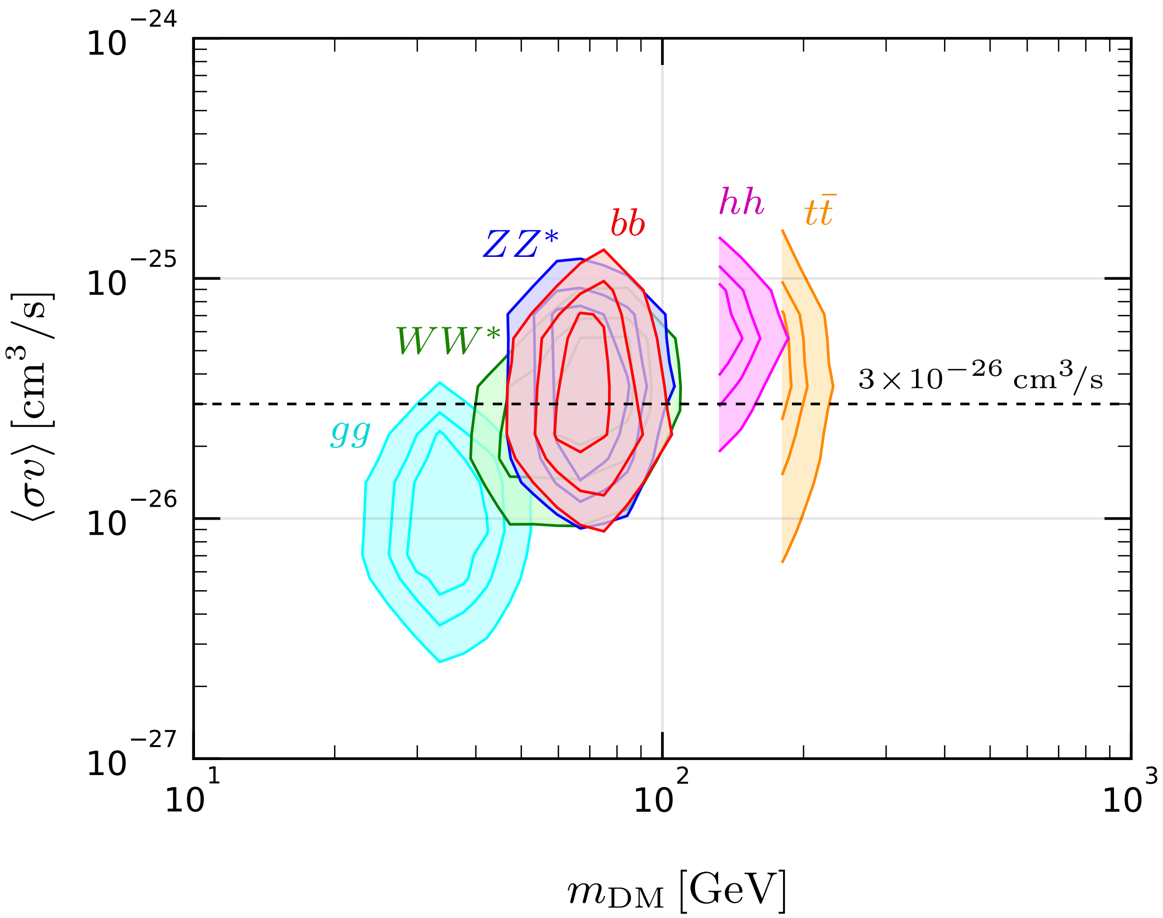
- Antiproton cross sections
  [Tan, Ng 1983; di Mauro, Donato, Goudelis, Serpico 2014; Kachelriess, Moskalenko, Ostapchenko 2015]
- Solar modulation
- Systematic uncertainties: Correlations in AMS data not published

II. Implications for dark matter models

Implications for other annihilation channels







channel	$\chi^2_{\rm CR}$
gg	50.3
$b\bar{b}$	45.8
$WW^{(*)}$	50.4
$ZZ^{(*)}$	45.6
hh	47.6
$t\bar{t}$	59.5

[Cuoco, JH, Korsmeier, Krämer 1704.08258]

Joint fit with Fermi-LAT gamma-ray data

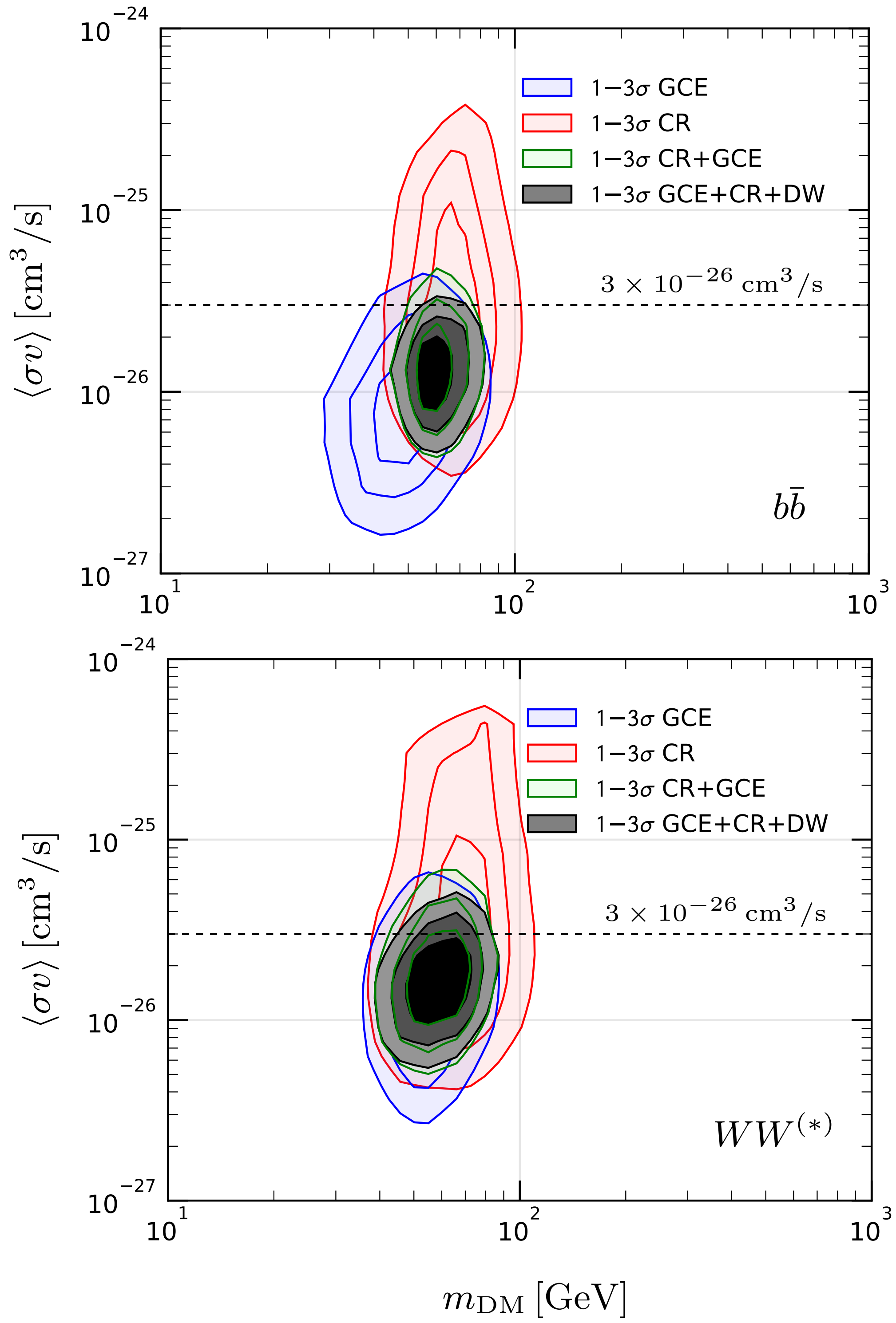
- **Limits from dwarfs galaxies**

  Used public likelihoods [Fermi-LAT 2017]

- **Dark matter interpretation of Galactic center excess (GCE)**

  - Used spectrum and covariance matrix from [Calore, Cholis, Weniger 2015]
  - *J*-factor from [Cuoco, Eintenеuer, JH, Krämer, 2016] $\log(J/\mathrm{GeV}^2\mathrm{cm}^{-5}) = 53.54 \pm 0.43$
  - Local DM density [Salucci, Nesti, Gentile, Martins, 2010] $\rho_\odot = 0.43 \pm 0.15$

	individual fits		joint fit	
channel	χ^2_{CR}	χ^2_{GCE}	χ^2_{CR}	χ^2_{GCE}
gg	50.3	20.8	52.0	31.6
$b\bar{b}$	45.8	21.2	47.9	23.5
$WW^{(*)}$	50.4	25.6	54.6	25.6
$ZZ^{(*)}$	45.6	25.0	45.8	25.9
hh	47.6	25.8	48.4	25.8
$t\bar{t}$	59.5	41.1	59.5	41.1



Joint fit with Fermi-LAT gamma-ray data

- Limits from dwarfs galaxies

  Used public likelihoods [Fermi-LAT 2017]

- Dark matter interpretation of Galactic center excess (GCE)

  - Used spectrum and covariance matrix from [Calore, Cholis, Weniger 2015]
  - J-factor from [Cuoco, Eintenener, JH, Krämer, 2016]
  - Local D… Martins…

Compatible with GCE and dwarfs

	individual fits		joint fit	
channel	$\chi^2_{\rm CR}$	$\chi^2_{\rm GCE}$	$\chi^2_{\rm CR}$	$\chi^2_{\rm GCE}$
gg	50.3	20.8	52.0	31.6
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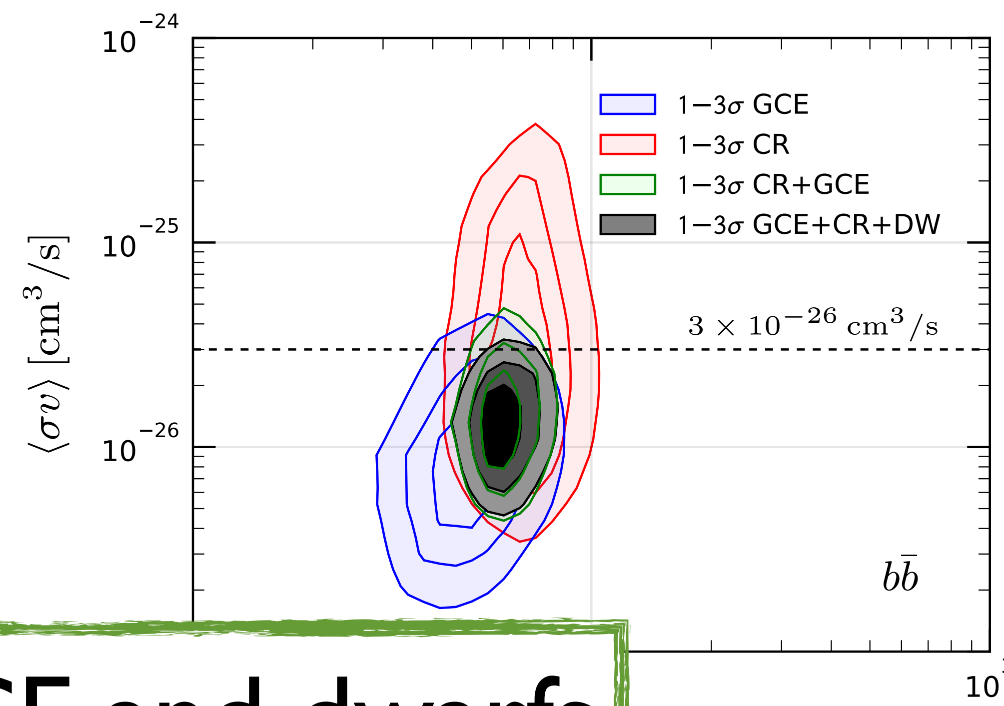
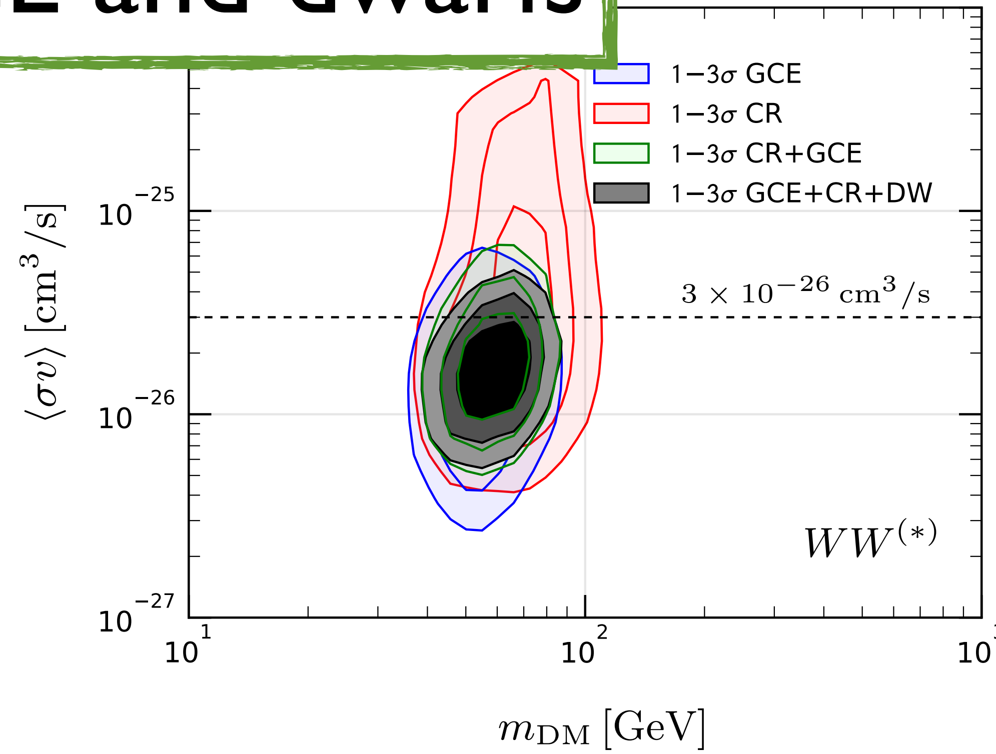
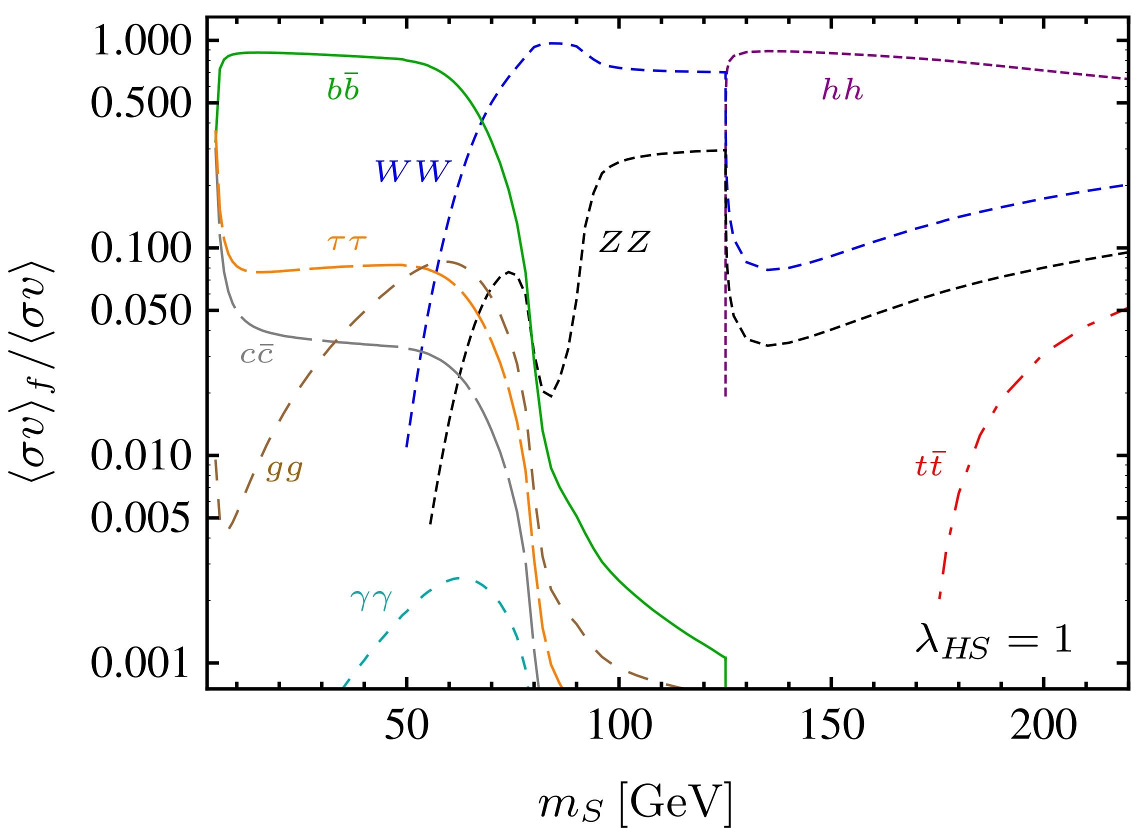




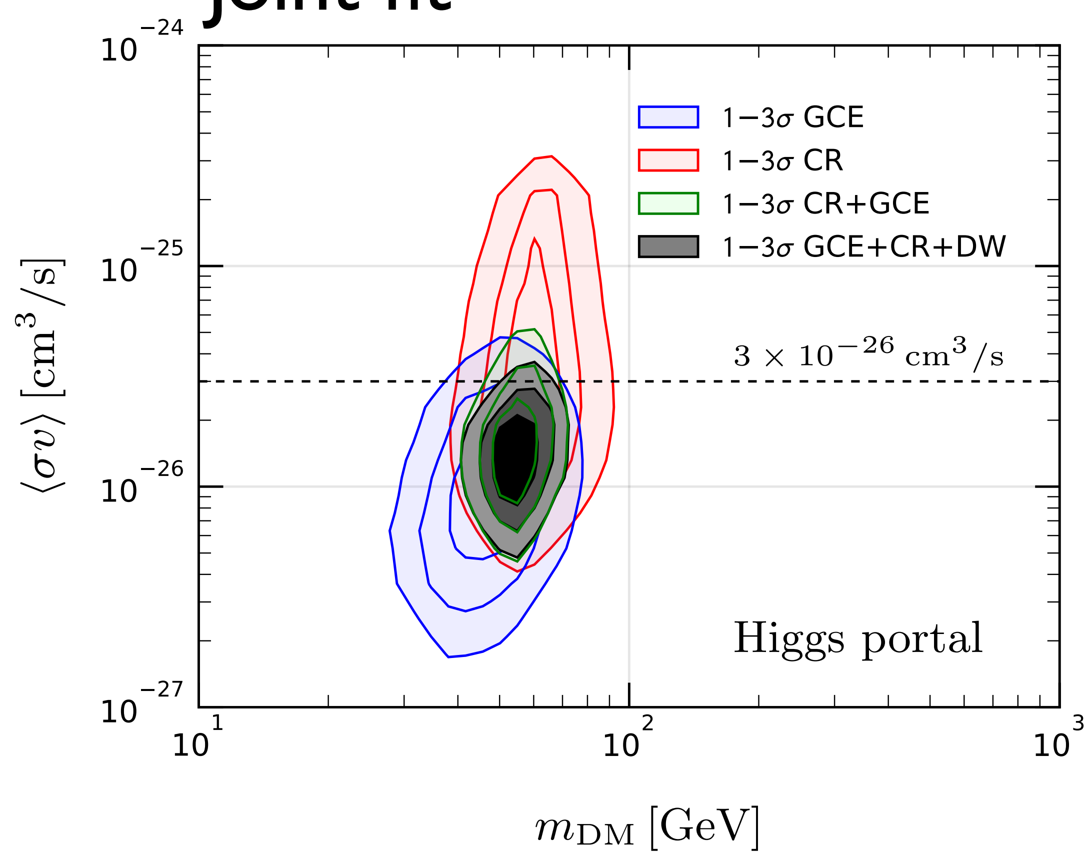
Implications for *realistic* models

- What does that imply for a full model?
- Consider general Higgs Portal model:

Relative weight of channels

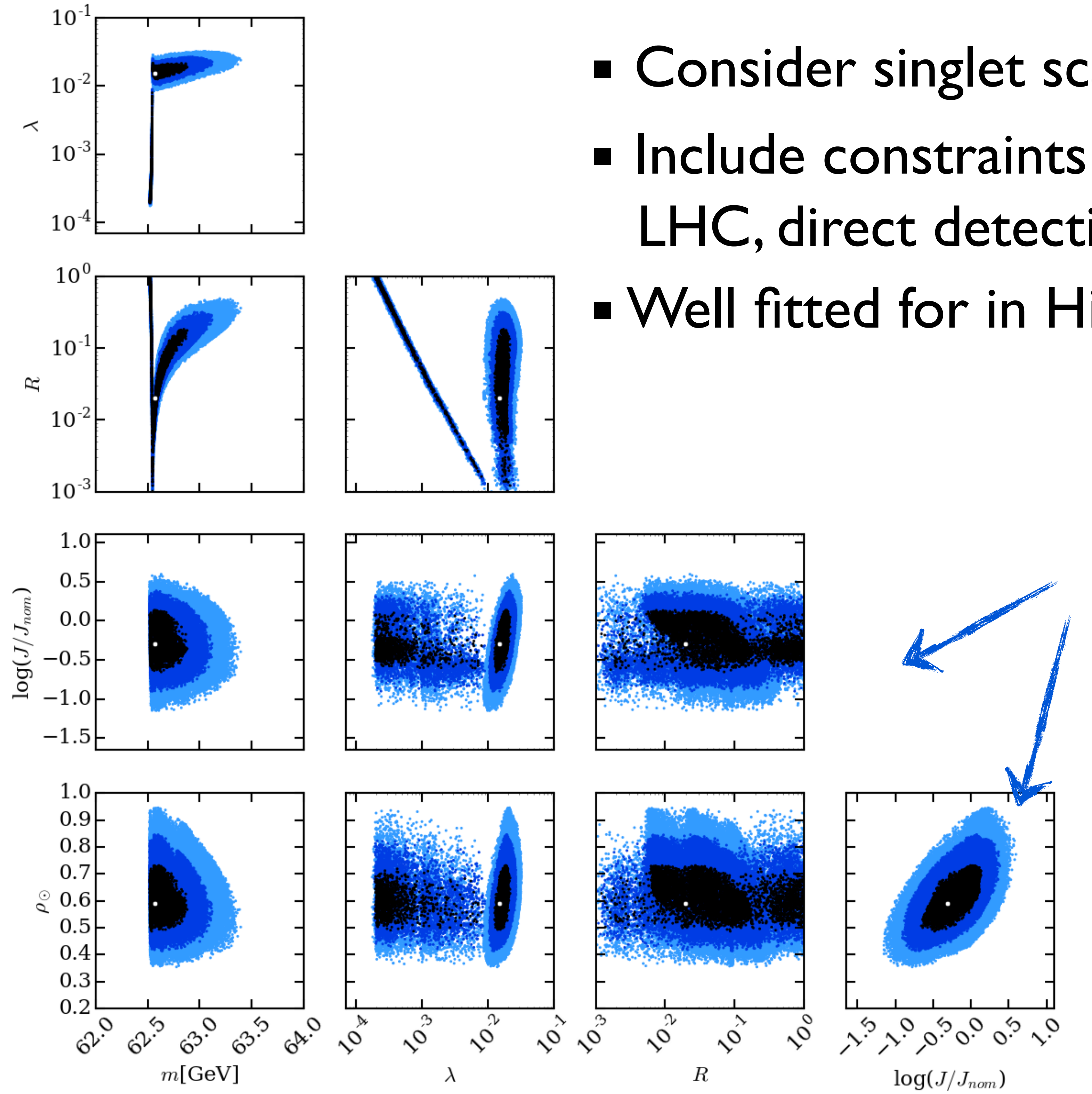


Joint fit



⇒ Points to dark matter masses of around 60 GeV ≃ $m_h/2$!

Implications for *realistic* models



- Consider singlet scalar Higgs Portal model:
- Include constraints from LHC, direct detection, relic density
- Well fitted for in Higgs funnel $m_{DM} \simeq m_h/2$

Fit prefers larger local DM density (somewhat smaller J-factor) than nominal values

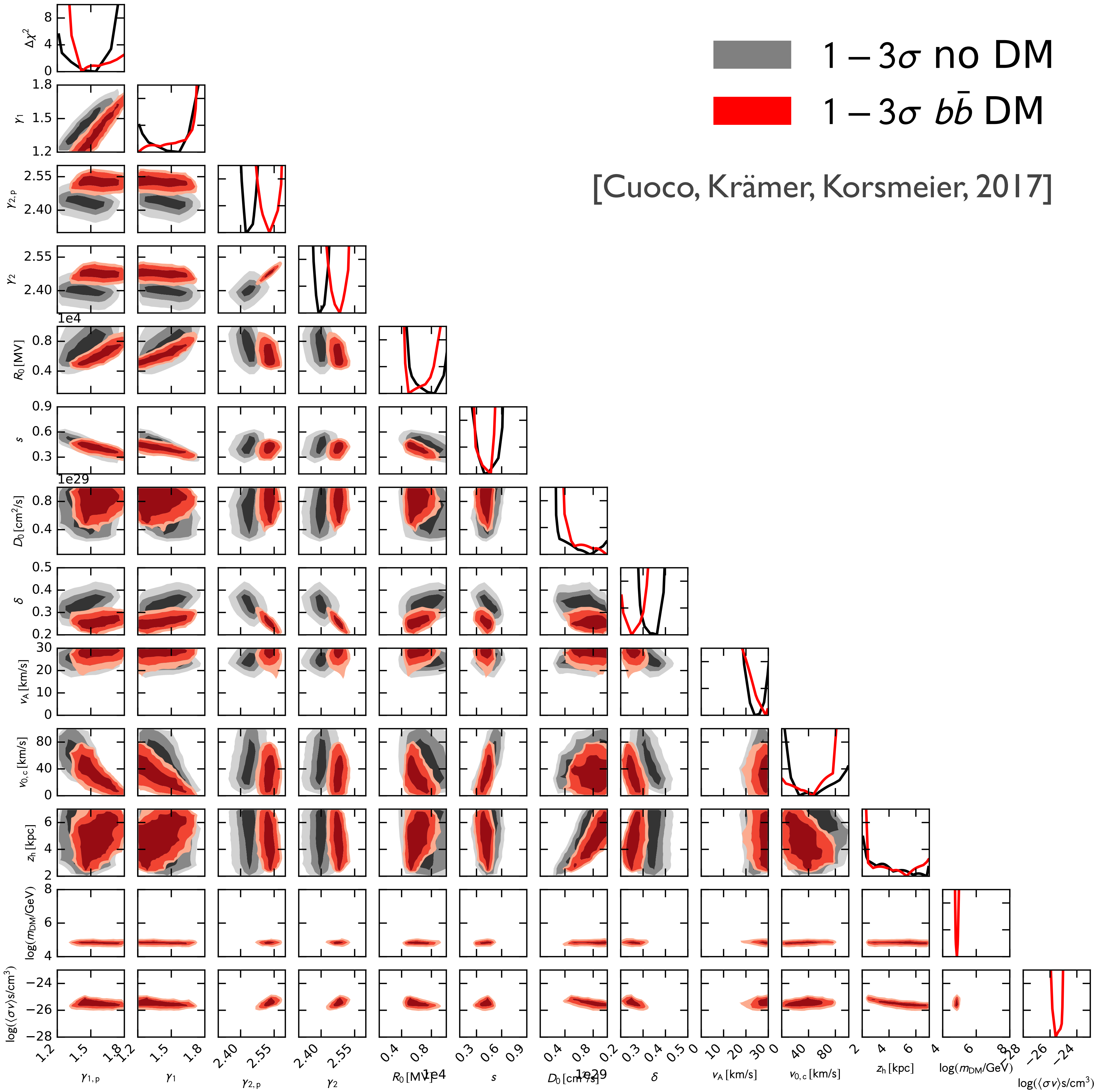
$$\rho_\odot = 0.43 \pm 0.15$$

$$\log(J/\text{GeV}^2\text{cm}^{-5}) = 53.54 \pm 0.43$$

Conclusions

- With AMS-02 cosmic-ray precision era started
- Reduce uncertainties w.r.t. MIN/MED/MAX scenario:
  $\Rightarrow$ Joint fit of propagation parameters and dark matter
- Feature in antiprotons: Possible hint for dark matter
- Systematic uncertainties:
  - Antiproton cross sections
  - Solar modulation
  - Correlations in AMS data
- Implications for dark matter models:
  - Compatible with GCE and dwarfs for several channels
  - Slight preference for larger local density
  - Joint fit in minimal Higgs Portal model

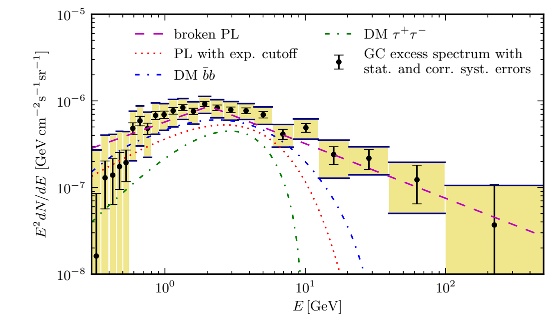
Backup



$1-3\sigma$ no DM
$1-3\sigma$ $b\bar{b}$ DM
[Cuoco, Krämer, Korsmeier, 2017]

χ^2-computation for the GCE

- Take measured spectrum d_i and covariance matrix Σ_{ij} from [Calore, Cholis, Weniger: 1409.0042]

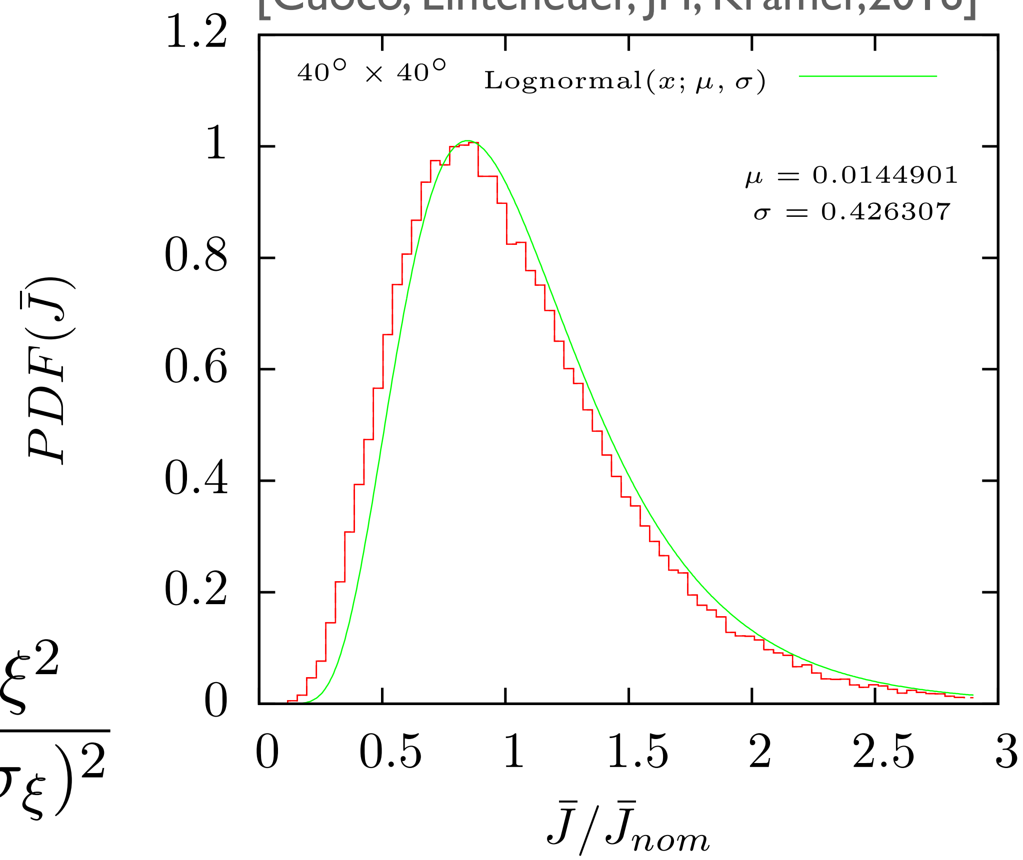


- Additional uncertainty on the theoretical prediction of the spectrum $\Sigma_{ij} \to \Sigma_{ij} + \Sigma_{ij}\delta_{ij}t_i^2\sigma_t^2\,, \quad \sigma_t = 10\%$ [Achterberg *et al.* 1502.05703]

- Large theoretical uncertainties on DM distribution in galaxy:
  - Take NFWc profile
  - Vary around best fit parameters with MC [from Calore, Cholis, Weniger: 1409.0042]

  ⇒ Distribution for *J*-factor
  - Determine σ_ξ for $\xi = \ln(\bar{J}/\bar{J}_{\rm nom})$

[Cuoco, Einteneuer, JH, Krämer,2016]



- Compute χ^2:

$$\chi^2 = \sum_{i,j}(d_i - e^{\xi}t_i)(\Sigma_{ij})^{-1}(d_j - e^{\xi}t_j) + \frac{\xi^2}{(\sigma_\xi)^2}$$